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We have fabricated optical channel waveguides in selectively masked planar GaAs/AlGaAs waveguide structures using MeV arsenic, carbon and oxygen ions without post implantation annealing. The fabricated channel waveguides were characterized exclusively by performing optical transmission measurements at wavelengths of 1.3 μm and 905 nm. Investigation of the extracted optical results reveals that further optimization of the ion beam parameters is required to reduce the high observed propagation loss values.

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Fabrication of Optical Channel Waveguides in the GaAS/AlGaAs System by Ion Beam Bombardment

Final Progress Report

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Fabrication of Optical Channels in Planar GaAs/AlGaAs Waveguides Using MeV Ions

FINAL REPORT- FEB 2000

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Abstract

Optical channels have been formed in selectively masked planar GaAs/AlGaAs waveguide structures using 10 MeV oxygen, 8 MeV carbon, and 8.5 MeV As ions. Implantation at different temperatures appears to have a direct effect on the propagation mode losses. Single-mode operation at 1.3 μm was observed from all the optical channels fabricated with O and C ions. The As ions were implanted into a different multiple quantum well (MQW) structure that was characterized at 905 nm. The optical characterization results provide insight as to which ion beam parameters are best suited to optimize this fabrication process.

Introduction

Developing new technology to fabricate reliable components for integration into high performance optoelectronic devices is of paramount importance. Recently, attention has been focused on utilizing III-V semiconductor waveguides in optoelectronic devices as either active or passive components. The interest has been motivated by the potential for monolithic integration of optoelectronic components in the computer and telecommunication industries.

A typical planar waveguide structure consists of a high index guiding layer bound on the top and bottom by layers of lower index material which form the cladding. Although planar waveguides allow the study of fundamental properties of materials, i.e., refractive index, structural changes, etc., practical devices require channel waveguide structures. There have been numerous techniques developed for fabricating channel waveguide geometries in the III-V system for implementation into optoelectronic integrated circuits (OEICs) [1,2].

Ion beam processing has become a widely used technique to create localized modifications in the band gap and refractive index of quantum well waveguide structures. Standard channel waveguide fabrication uses a mask to define the optical channel to be created via ion beam processing. The advantage of ion beam processing is the ability to control the beam parameters, and thus the material properties, precisely.

Changes in the refractive index induced by ion beams can provide lateral waveguide confinement of light through the guiding region. Typically, ions beams at energies of 5 to 800 keV are used in the GaAs/AlGaAs system [3-5]. The present research employed MeV ions to fabricate

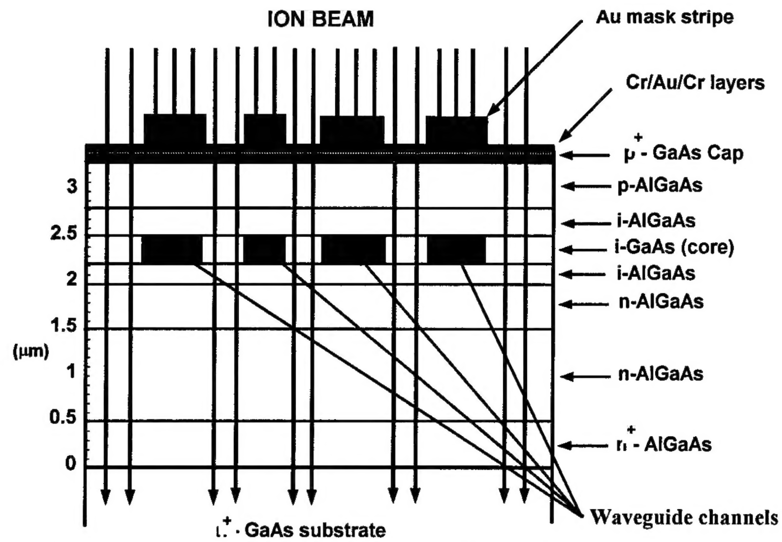

Figure 1. Schematic of the waveguide channels fabricated by high energy ion bombardment.

Figure 1. Schematic of GaAs/AlGaAs waveguide structure.

optical channels in a planar GaAs/AlGaAs waveguide. The effects that ion fluence, current and annealing temperature have on the optical properties will be discussed.

Experiments

The waveguide structures investigated in this study were grown by Molecular Beam Epitaxy (MBE) on exact (100) oriented Si-doped GaAs substrates. For the O and C implants the high index guiding layer (core) consisted of pure 0.3 μm of GaAs bound on the top by a 0.8 μm thick $Al_{0.4}Ga_{0.6}As$ layer and on the bottom by a 1.7μm thick $Al_{0.4}Ga_{0.6}As$ layer to form the low index cladding. This structure, illustrated in Figure 1, operated as suitable planar waveguides at a wavelength of 1.3 μm. The cladding layers were doped p and n-type because the waveguide and mask were originally designed to investigate the electro-optical properties of the device. The doping is irrelevant to the purpose of this work and had no effect on the results.

A second MQW structure was grown for this project at Sandia National Laboratory, Los Alamos, New Mexico. The design is based upon a single mode MQW AlGaAs/GaAs strucuture grown and optically characterized by Bloemer and Myneni [6] Figure 2 shows a schematic of the device. The surface is a 100 nm GaAs cap on a 750 nm Al.24Ga.76As upper cladding. Next come 48 quantum wells of 14 nm Al.3Ga.7As/7 nm GaAs with a total thickness of 1008 nm. The bottom cladding is 750 nm followed by a 500 nm GaAs buffer on the (100) GaAs substrate. The Al levels and thickness are such that the device guides at wavelengths longer than 870 nm. This device differs from that of Bloemer and Myneni only in that no dopants were introduced to provide electro-optic effects.

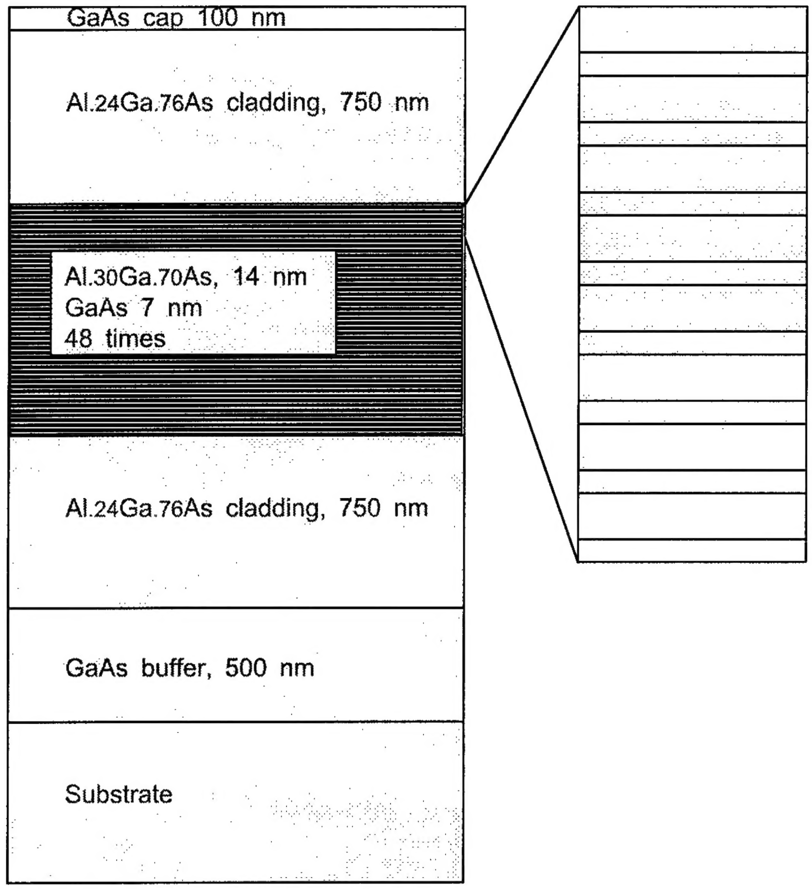

Figure 2. Schematic of the MQW structure grown at Sandia National Laboratory, Used for As implantation.

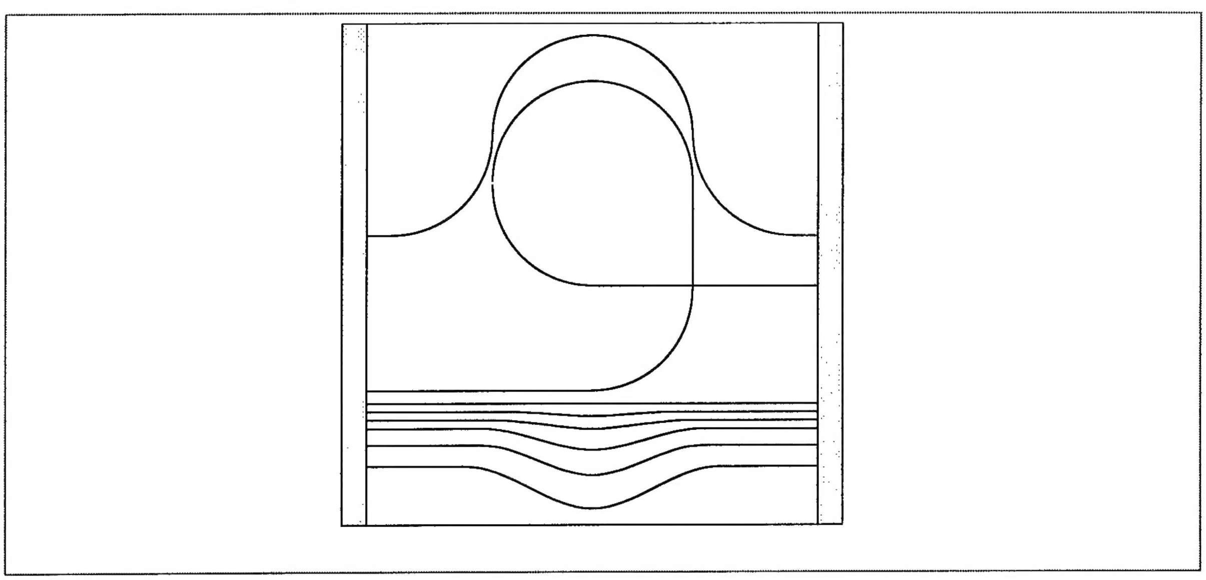

Figure 3. Schematic of mask designed for fabrication of curved waveguides..

Prior to irradiation gold stripes were electroplated onto the wafer surface to serve as an implantation mask. Two different masks are being used for these implantations. The first consists of a series of parallel stripes, 5 to 10 μm wide, 35 to 40 μm apart. The second, Figure 3, has 4 μm wide stripes that incorporate a varying degree of bend; ranging from none to 90 degree constant radius bends and a loop. The pattern is 10 mm x 10 mm resulting in waveguides 10 to 22.5 mm long. The pattern has been designed but the mask is yet to be fabricated.

The Au stripes were 5-10 μm wide and nearly 5 μm thick. The gold is thick enough, as determined using the Monte-Carlo simulation code TRIM [7], to stop the MeV ions. The region beneath the mask is unmodified and remains a waveguide. In the open areas the ions penetrate completely through the waveguide region and stop at least 1 to 3 μm below the waveguide. Doping is thus not responsible for changes in the electrical properties of the material. The intermixing is driven by the thermal migration of defects created by the ions passing through the material [8]. This effect leads to enhanced intermixing when the implantation is performed at elevated temperatures. In the waveguide region the ions interact almost exclusively with the host's electrons in a process known as electronic stopping. This process generates few direct atomic displacements but creates a great deal of ionization and phonons.

The first series of irradiation experiments were performed using 10 MeV oxygen and 8 MeV carbon ions at fluences ranging from $1.2x10^{14}$ to $5.8x10^{15}$ ions/cm^2. The ion beam current densities were varied from 0.8 to 1.4 μA/cm^2. After irradiation the channel waveguides were optically characterized at 1.3 μm using end fire coupling, as shown in Figure 4. Light from a laser diode source was coupled into the channel regions by focusing the beam onto a cleaved face of the waveguide sample. A polarizing beam splitter was employed to obtain either TE or TM modes during analysis. A microscope objective imaged the output onto an IR camera for visual observation or onto an IR detector for quantitative measurements. The captured images yielded both width and depth mode profiles.

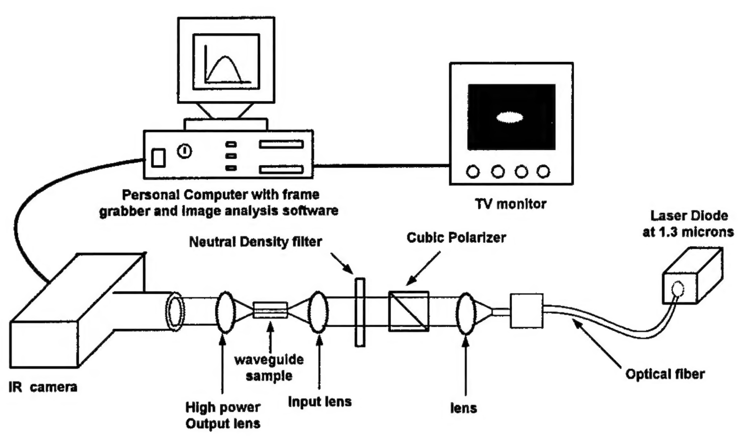

Figure 4. Schematic of optical characterization system used to measure waveguides losses..

Figure 5 shows the transmission mode output intensity mode profile which was typically observed on all the fabricated channels. The mode size at the FWHM was determined to be less than 3 μm, which is smaller than the gold mask widths of 5-10 μm. Straggling effects can be large if the lateral confinement dimensions are comparable to the range of ion straggling. High energy ion beams reduce straggling effects in the waveguide region. As a result, adjacent lateral straggling of the ions beneath the gold mask stripes do not overlay and destroy the optical channels.

Single TE mode operation was observed from all the samples examined directly after each irradiation treatment with O and C.

Implantation with 8.5 MeV arsenic was chosen for the waveguide structure grown for this project by Sandia National Laboratory. Arsenic was selected because there are no doping issues with As and it has been used in other MeV ion beam mixing research [9]. The energy is sufficient for the As ions to completely pass through the MQW structure yet be stopped by 2.5 μm of Au. The range of 8.5 As is 3.1 μm in GaAs and 1.5 μm in Au.

Gold implantation masks have been applied to two sets of samples and the samples irradiated with 8.5 MeV As at room temperature, 200°C and 400°C. Fluences were 1e13, 2.5e13, and 2.5e14/cm^2 at each temperature. The current of As^{5+} was maintained at 30 to 40 nA/cm^2. This current is the average current measured on the sample as the beam is rapidly scanned across the sample. This current density was selected based on research by Charbonneau, et al., [9] investigating the change in the band gap energy in MeV As bombarded AlGaAs structures. The first set of nine samples had to be rejected due to a 45° misalignment of the mask. The misalignment prevented cleaving the wafer perpendicular to the waveguide. Attempts to use a high quality dicing saw that normally produces optical quality edges to create end faces suitable for optical coupling

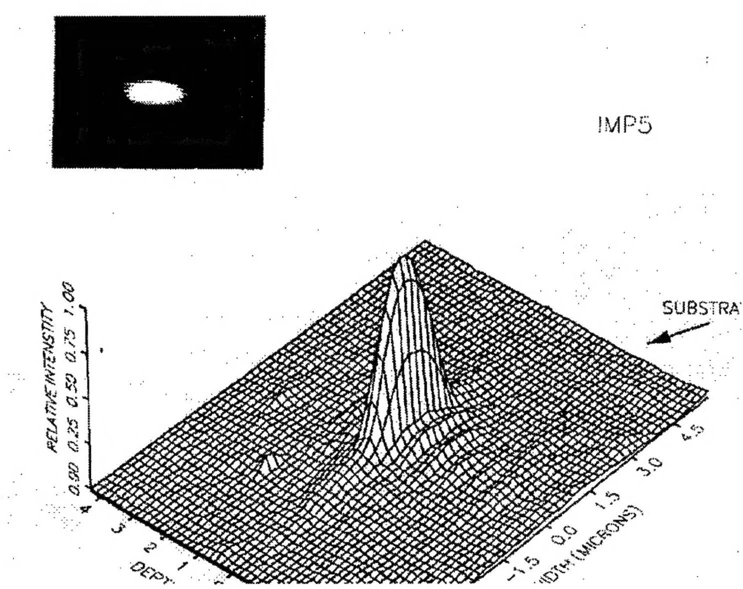

Figure 5. Output image from channel waveguide, top, surface plot of intensity distribution of output image, bottom.

were unsuccessful. Another mask was applied to a section of the original wafer and small samples approximately 1-2 mm wide and 4 mm long were cut for implantation. The implantation was repeated in December, 1998 at ORNL. The mask pattern that includes curved waveguides was delayed until more definite results could be obtained from the straight waveguides. Preliminary tests at MICOM on these samples showed no waveguiding at 1.3 μm. It was supposed that the Au mask was too thin and the ions had penetrated to the intended channel waveguide region. With several milliwatts of power applied weak guiding was noted in the unmasked region, which indicated incomplete intermixing for that particular sample. Under the masked region, instead of a bright, channeled waveguide mode appearing on the output screen, a black spot surrounded by scattered light was seen. This indicated complete absorption under the masked region. The initial hypothesis was that the Au mask was too thin and some As ions had stopped in the waveguide region.

Only preliminary work could be carried out at the MICOM facility due to restricted access and time pressures on the workers there. It was decided to carry out the waveguideing at AAMU. A 5 mW, 905 nm diode laser was acquired to work better with the Sandia supplied waveguide, as it had been designed to function in the 880 to 1000 nm range. The laser functioned for a month before failing. It was one of a batch of defective lasers. Replacement took three months. In order to assist in the optical set up an IR viewer was also purchased. This supplemented the CCD camera that had been used and greatly eased the alignment process.

Another Au mask was applied to a portion of the Sandia Laboratory provided AlGaAs wafer and more samples were implanted in April, 1999 at Oak Ridge National Laboratory. The fluences and temperatures were kept the same as in the previous As implantation but the energy was changed to 5 MeV to ensure that no ions would penetrate the mask. TRIM calculations showed that this energy was sufficient to let the ions pass completely through the waveguide region.

Several of the newly implanted samples were cleaved to the appropriate 1 to 1.5 mm length but none showed signs of waveguiding. Some of this could be attributed to the poor quality of cleaving of these samples. When the well cleaved sample that showed absorption at 1.3 μm was placed into the set up at AAMU waveguiding was observed in the masked region and no waveguiding was seen in the unmasked region. This discrepancy is most likely due to the different wavelengths used. The sample was designed to operate at 905 nm rather than 1.3 μm. This was the only sample to show strong evidence of channel waveguide formation after arsenic bombardment. The losses of this waveguide were extremely high. Several more samples were cleaved and clean edges obtained. The losses of these guides were also extremely high. The guides had to less than 1 mm long in order to obtain any detectable output. The result of the second set of implants was that the losses remained unacceptably high.

Irradiating the waveguide structures at temperatures below room temperature did not prevent single mode channels from forming. TE mode loss values for each channel waveguide are recorded in Table 1. The propagation losses were calculated after measuring the insertion loss and then subtracting the estimated coupling loss due to mode mismatch and Fresnel reflection for each waveguide sample of known length. The variation of the recorded TE mode losses can be directly linked to the variation of the chosen ion beam parameters.

The TE mode losses can be associated with the ability of the ions to produce effective lateral confinement barriers. Increasing the beam current density, Samples A and B, resulted in a reduction of the TE mode loss. The probable explanation for this is that the faster the waveguide structure receives ions the more pronounced the degree of irradiation damage.

Sample	Energy and Ion species	Fluence (ions/cm^2)	Current Density (μA/cm^2)	As Implanted Temperature (K)	TE Mode Loss (dB/mm)
A	8MeV carbon	1.2x10^{14}	0.8	300	14.1
B	8MeV carbon	1.2x10^{14}	1.4	300	9.2
C	8MeV carbon	5.8x10^{15}	1.1	300	5.8
D	8MeV carbon	1.2x10^{14}	1.1	84	14.1
E	10MeV oxygen	2.2x10^{15}	0.8	300	10.7
F	10MeV oxygen	1.2x10^{15}	0.8	686	9

Results from sample C show that by increasing the ion fluence while maintaining similar beam current densities as samples A and B the TE mode loss was further reduced. At a temperature near LN_2 no significant change occurred for the TE mode loss for sample D which was irradiated using similar beam current densities as samples A through C. Elevating the substrate temperature during the irradiation process using a heavier ion species showed the opposite effect on the TE mode loss values. Sample F displayed a slightly lower TE mode loss value than sample E under

Table 1. Experimental ion beam parameters and propagation mode loss values.

similar irradiation conditions. These results provide insight as to which ion beam parameters will be more effective at reducing the mode losses during future irradiation experiments.

Conclusion

We have fabricated optical channel waveguides in planar GaAs/AlGaAs waveguide structures using high energy oxygen and carbon ions. The propagation mode losses associated with the selected ion beam parameters suggest that further optimization is necessary. Intermixing with high energy As ions formed waveguides but with unacceptably high propagation losses.

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